g-2 Nitrogen Purge Cylinder Securement and Safety Analysis

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This document describes the method for securing eight nitrogen cylinders to the cylinder rack and web of the Emmert shipping fixture. Calculations were performed for stress of involved components, and additional safety precautions are explained. The figure below shows the four cylinders attached to the shipping fixture, there are 4 more on the opposite side of the girder attached using the same methods. There are 6 failure modes all listed and addressed below. This analysis concludes the attachment method is secure and ensures safe transport of the cylinders.

Failure Modes:

1.) Shearing of bolts securing cylinder racks to web of girder.	***(Side Load g forces)***
2.) Bending stress of strut channel	***(Fore/Aft g forces)***
3.) Tensile stress in threaded rods securing strut channel	***(Fore/Aft g forces)***
4.) Cylinders sliding vertically upwards out of containment position	***(Vertical g forces)***
5.) Wedging Effect from Cylinder Rack	***(Side Load g forces)***
6.) Other objects falling and striking/damaging cylinder valves	***(External Hazards)***

Scenario #1

Shearing of bolts securing cylinder racks to web of girder. ***(Side Load g forces)***

For this scenario we will exert the side force of all four cylinders on one side of the girder at a 1g acceleration to one of the 5/16" bolts which secures the cylinder rack to the web of the girder. In reality there are four bolts per rack and two racks. Since there are 8 bolts total, and we apply the load to only one, this calculation is conservative

Shear area of a 5/16" coarse series bolt

$Area_{bolt\_0.0313} := 0.0454in^2$ *From Shigley's M.E. Design: Table 8-2*

Yield stress of grade 2 bolt:

$\sigma_{yield\_Grade2Bolt} := 55ksi$

Full Cylinder Weight:

$Cylinder_{mass} := 119lb$ $N_{2mass} := 15lb$ $Total_{Load} := 4\cdot(Cylinder_{mass} + N_{2mass})$

$Force_{side} := Total_{Load}\cdot 1g = 536\,lbf$

Bolt shear stress *Percentage of yield*

$\sigma_{shear} := \dfrac{Force_{side}}{Area_{bolt\_0.0313}} = 11.806\,ksi$ $\dfrac{\sigma_{shear}}{\sigma_{yield\_Grade2Bolt}} = 21.466\,\%$ *Failure mode #1 addressed.*

Scenario #2

Bending stress of strut channel ***(Fore/Aft g forces)***

For this scenario we will exert the fore/aft force of all four cylinders on one side of the girder at a 1g acceleration to the entire 48" length of strut channel which compress the cylinders tightly against the cylinder rack. In reality the span in between each cylinder is only 12" and since we apply the load to the full span, this calculation is conservative

Shear area of a 5/16" coarse series bolt (minor diameter)

$Area_{bolt\_0.0313} := 0.0454in^2$ *From Shigley's M.E. Design: Table 8-2*

Yield stress of A36 grade steel

$\sigma_{yield\_A36} := 36ksi$

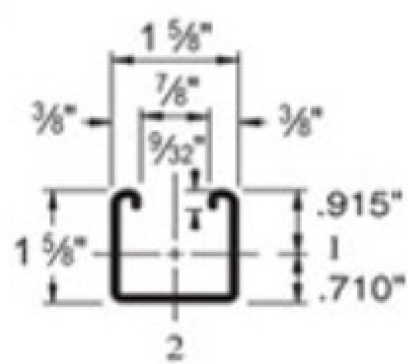
Full strut channel span, and distributed load:

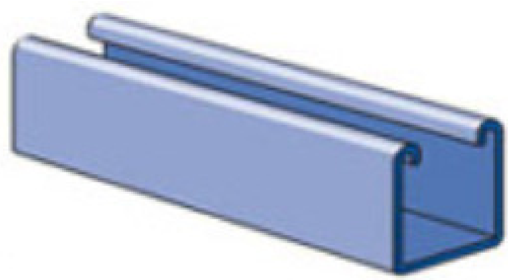
$span := 48in$

$distributed_{weight} := \frac{Total_{Load} \cdot 1g}{span} = 134 \frac{lbf}{ft}$

Dimensions of strut: *Source: http://www.unistrutohio.com/products/p1000.html*

Unistrut P1000 - 1-5/8" x 1-5/8"





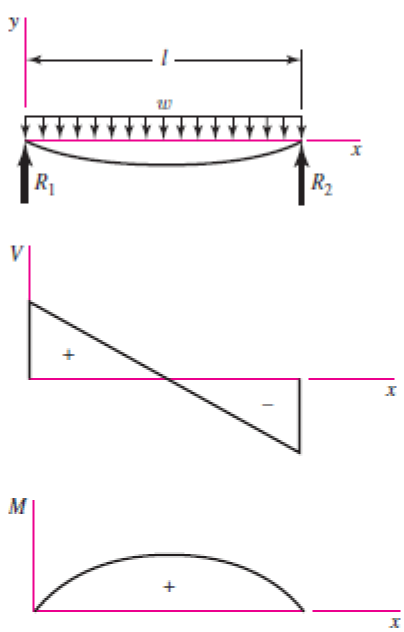
$I_{xx} := 0.185in^4$

$dist_{n.axis} := 0.915in$

$area_{strut} := 0.555in^2$

Beam Loading:

7 Simple supports—uniform load



$$R_1 = R_2 = \frac{wl}{2} \qquad V = \frac{wl}{2} - wx$$

$$M = \frac{wx}{2}(l - x)$$

$$y = \frac{wx}{24EI}(2lx^2 - x^3 - l^3)$$

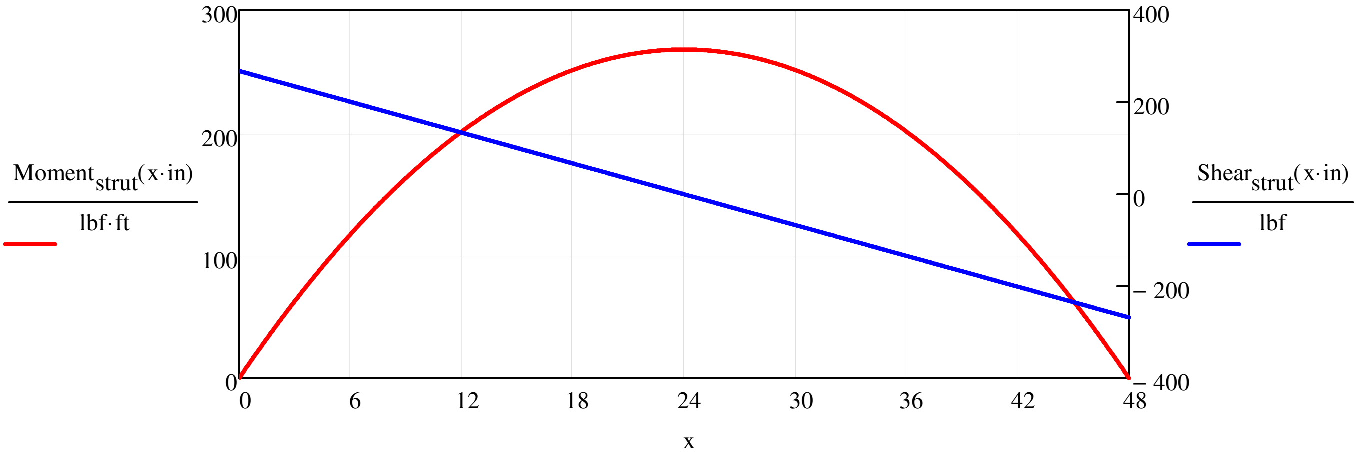
$$y_{max} = -\frac{5wl^4}{384EI}$$

Shear load

$$Shear_{strut}(x) := \frac{distributed_{weight} \cdot span}{2} - distributed_{weight} \cdot x$$

Moment load

$$Moment_{strut}(x) := \frac{distributed_{weight} \cdot x}{2} \cdot (span - x)$$



$$\sigma_{shear} := \frac{-Shear_{strut}(span)}{area_{strut}} = 0.483\,ksi$$

$$\sigma_{bending} := \frac{Moment_{strut}\left(\frac{span}{2}\right) \cdot dist_{n.axis}}{I_{xx}} = 15.906\,ksi$$

Max Principal Stress

$$\sigma_{max} := \sqrt{\sigma_{bending}{}^2 + \sigma_{shear}{}^2} = 15.913\,ksi$$

Percentage of yield

$$\frac{\sigma_{max}}{\sigma_{yield\_A36}} = 44.204\,\%$$

In reality the span is only 12", not 48" so the real stress would be only 6% of what we calculate here:

$span := 12in$

$$\sigma_{bendingReal} := \frac{\frac{distributed_{weight} \cdot \left(\frac{span}{2}\right)}{2} \cdot \left(\frac{span}{2}\right) \cdot dist_{n.axis}}{I_{xx}} = 0.994\,ksi$$

$$\frac{\sigma_{bendingReal}}{\sigma_{yield\_A36}} = 2.761\,\%$$

Failure mode #2 addressed.

Scenario #3

Tensile stress in threaded rods securing strut ***(Fore/Aft g forces)***

For this scenario we will exert the fore/aft force of all four cylinders on one side of the girder at a 1g acceleration to one of the 3/8" threaded rods which hold the piece of strut which holds the cylinders tightly against the cylinder rack. In reality there are 5 threaded rods all sharing the load, since we apply the load to only one, this calculation is conservative

Tensile area of a 3/8" coarse series threaded rod

$Area_{bolt\_0.0375} := 0.0775in^2$ *From Shigley's M.E. Design: Table 8-2*

Yield stress of grade 2 bolt:

$\sigma_{yield\_Grade2Bolt} := 55ksi$

Full Cylinder Weight:

$Force_{fore\_aft} := Total_{Load} \cdot 1g = 536\,lbf$

Bolt Tensile stress *Percentage of yield*

$\sigma_{tensile} := \dfrac{Force_{side}}{Area_{bolt\_0.0375}} = 6.916\,ksi$ $\dfrac{\sigma_{tensile}}{\sigma_{yield\_Grade2Bolt}} = 12.575\,\%$ *Failure mode #3 addressed.*

Scenario #4

Cylinders sliding vertically upwards out of containment position ***(Vertical g forces)***

For this scenario we will turn the entire assembly upside down to see if the cylinders slip out of their fastened position with a 1g vertical load upwards. In reality the minimum vertical acceleration is expected to be 0.65 g, still in the downward direction, making this negative 1g acceleration calculation very conservative since it is not a credible failure scenario anyways.

Relationship between bolt torque and bolt tension

$Torque = K_{factor} \cdot Force_{tension} \cdot d_{thread}$ *From Shigley's M.E. Design: equation 8-27*

$Torque := 15lbf \cdot ft$ $K_{factor} := 0.2$ $d_{thread} := 0.375in$

$Force_{tension} := \dfrac{Torque}{K_{factor} \cdot d_{thread}} = 2400\,lbf$

Coefficient of friction between plastic and steel   Source: http://www.tribology-abc.com/abc/cof.htm

$\mu := 0.25$

Force of up-side down cylinder:

$cylinder_{mass} := 134lb$

$cylinder_{weight} := cylinder_{mass} \cdot 1g = 134\,lbf$

Force required to cause slipping

$Slip_{force} := Force_{tension} \cdot \mu = 600\,lbf$

Percentage of slip force

$\frac{cylinder_{weight}}{Slip_{force}} = 22.333\,\%$

Failure mode #4 addressed.

Scenario #5

Wedging Effect from Cylinder Rack   (Side Load g forces)

Here we calculate the tensile force on the threaded rod and strut channel due to the wedging effect of the cylinder rack creating force 90 degrees from the acceleration direction. This wedging effect results in a tensile load on the threaded rod and a bending stress in the strut channel. We use 1g acceleration for this calculation, but the maximum design g force was 0.762 g, making this a conservative calculation:

Rack and cylinder dimensions, and calculated radius of cylinder travel is moving along cylinder rack.

$diameter_{rack} := 12in$ $diameter_{cylinder} := 9in$ $diameter_{path} := diameter_{rack} - diameter_{cylinder}$

Mean diameter of 3/8" threaded rod

$d_{major} := 0.375in$ $d_{minor} := 0.3344in$

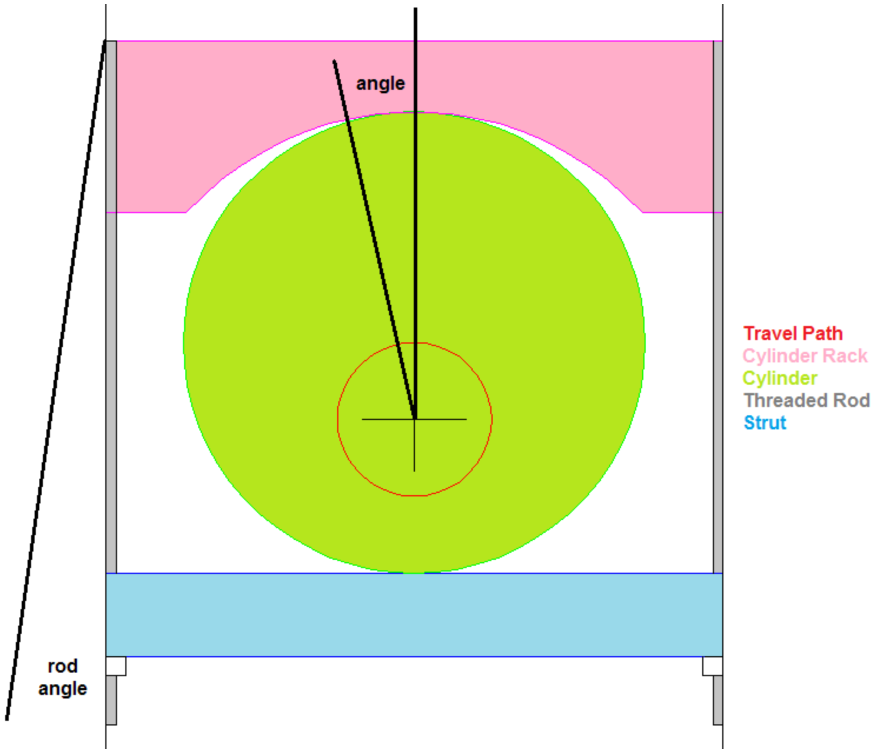
$r_{rod.mean} := \frac{d_{major} + d_{minor}}{4} = 0.177\,in$ $area_{mean} := \pi \cdot r_{rod.mean}^{2}$ $E_{steel} := 200GPa$ $length_{rod} := 12in$

Sideways force on cylinders must equal its weight at 1g

$cylinder_{Force} = 5force_{sideways}$ $cylinder_{mass} \cdot 1g = 134\,lbf$

$cylinder_{Force} = (PreTension + WorkingTension) \cdot \sin(rack_{angle}) + WorkingTension \cdot \sin(rod_{angle}) + rod_{bendingForce}$

Figure showing Top view of securement method and angle terminology:



Iterated working stress and angle to achieve specified side force criteria

$PreTension := 2400lbf \qquad WorkingTension := 491lbf \qquad angle := 2.45deg \qquad rod_{angle} := 0.612deg$

$$(PreTension + WorkingTension)\cdot \sin(angle) + WorkingTension\cdot \sin\left(rod_{angle}\right) + rod_{bendingForce} = 134\,lbf$$

side force correct

Calculate displacement based off this side force

$$displacement_{CylinderSideways} := radius_{path}\cdot \sin(angle) = 0.064\,in$$

$$displacement_{RodEndSideways} := displacement_{CylinderSideways}\cdot 2 = 0.128\,in$$

$$displacement_{axial} := -\sqrt{radius_{path}^{\ 2} - displacement_{CylinderSideways}^{\ 2}} + radius_{path} = 0.00137\,in$$

$$rod_{angle} := atan\left(\frac{displacement_{RodEndSideways}}{length_{rod}}\right) = 0.612\,deg$$

Calculate Strain on threaded rod

$$\varepsilon_{rod} := \frac{\left[\left(length_{rod} + displacement_{axial}\right)^2 + displacement_{RodEndSideways}^2\right]^{\frac{1}{2}}}{length_{rod}} - 1 = 0.00017$$

Calculate working and total tensile force and stress on threaded rod:

$$Force_{tensile} := area_{mean} \cdot E_{steel} \cdot \varepsilon_{rod} = 491\,lbf$$

$$\sigma_{TensileWorking.rod} := \frac{Force_{tensile}}{Area_{bolt\_0.0375}} = 6.338\,ksi$$

$$Force_{TotalTensile} := Force_{tensile} + PreTension = 2891\,lbf$$

$$\sigma_{TotalTensile.rod} := \frac{Force_{TotalTensile}}{Area_{bolt\_0.0375}} = 37.305\,ksi$$

Bending side force and stress on threaded rod

$$I_{xx.rod} := \frac{\pi}{4} \cdot r_{rod.mean}^{4}$$

$$rod_{bendingForce} := \frac{displacement_{RodEndSideways} \cdot \left(3 \cdot E_{steel} \cdot I_{xx.rod}\right)}{length_{rod}^{3}} = 5.018\,lbf$$

$$\sigma_{bending.rod} := \frac{rod_{bendingForce} \cdot length_{rod} \cdot \frac{0.3344in}{2}}{I_{xx.rod}} = 12.958\,ksi$$

Maximum principal stress of threaded rod is below yield of the weakest threaded rod available :

$$\sigma_1 := \sigma_{bending.rod} + \sigma_{TotalTensile.rod} = 50.263\,ksi$$

$$\frac{\sigma_1}{\sigma_{yield\_Grade2Bolt}} = 91.388\,\%$$

Calculate bending stress in strut channel

$$\sigma_{bendingStrut} := \frac{\frac{Force_{TotalTensile}}{8} \cdot \left(4 \cdot \frac{span}{2} - span\right) \cdot dist_{n.axis}}{I_{xx}} = 21.449\,ksi$$

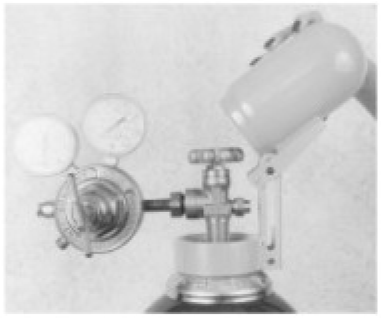
$$\frac{\sigma_{max}}{\sigma_{yield\_A36}} = 44.204\,\%$$

Failure mode #5 addressed.

Scenario #6

Other objects falling and striking/damaging cylinder valves (External Hazards)

For this scenario we simply explain the method for protecting the valve caps from damage from external sources. Protective caps, seen below, will be used during transport: The valve caps are part #GRF GT11, purchased from WelderSource.com, link below:



http://store.weldersource.com/p-3140-griftan-hi-pressure-safety-cap.aspx?gclid=CJfX0ve437cCFY1DMgodFFEApA

Failure mode #6 addressed.

All 6 Failure modes were addressed; this analysis concludes the attachment method is secure and ensures safe transport of the cylinders.